Decision making in the presence of uncertainty

Computing the probability of some event may not be our ultimate goal.

Instead we are often interested in making decisions about our future actions so that we satisfy some goals.

Example: medicine

- Diagnosis is typically only the first step.
- The ultimate goal is to manage the patient in the best possible way. Typically many options available:
  - Surgery, medication, collect the new info (lab test).
  - There is an uncertainty in the outcomes of these procedures: patient can be improve, get worse or even die as a result of different management choices.
Decision-making in the presence of uncertainty

Main issues:
• How to model the decision process with uncertain outcomes in the computer?
• How to make decisions about actions in the presence of uncertainty?

The field of decision-making studies ways of making decisions in the presence of uncertainty.

Decision making example.
Assume we want to invest $100 for 6 months
• We have 4 choices:
  1. Invest in Stock 1
  2. Invest in Stock 2
  3. Put money in bank
  4. Keep money at home

Stock 1 value can go up or down:
Up: with probability 0.6
Down: with probability 0.4

100
Stock 1
Stock 2
Bank
Home

0.6
0.4
110
90

M. Hauskrecht
Decision making example.

Assume we want to invest $100 for 6 months

- We have 4 choices:
  1. Invest in Stock 1
  2. Invest in Stock 2
  3. Put money in bank
  4. Keep money at home

Stock 1 value can go up or down:
- Up: with probability 0.6
- Down: with probability 0.4

Monetary outcomes for up and down states

Investing of $100 for 6 months

Monetary outcomes for different states
**Decision making example.**

We need to make a choice whether to invest in Stock 1 or 2, put money into bank or keep them at home. But how?

<table>
<thead>
<tr>
<th></th>
<th>Stock 1</th>
<th>Stock 2</th>
<th>Bank</th>
<th>Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monetary outcomes for different scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(up)</td>
<td>0.6</td>
<td>0.4</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(down)</td>
<td>0.4</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>140</td>
<td>80</td>
<td>101</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Assume a simplified problem with the Bank and Home choices only.**

The result is guaranteed – the outcome is deterministic

What is the rational choice assuming our goal is to make money?
Decision making. Deterministic outcome.

Assume a simplified problem with the Bank and Home choices only.
These choices are deterministic.

Our goal is to make money. What is the rational choice?

**Answer:** Put money into the bank. The choice is always strictly better in terms of the outcome

But what to do if we have uncertain outcomes?

---

Decision making. Stochastic outcome

- **How to quantify the goodness of the stochastic outcome?**
  We want to compare it to deterministic and other stochastic outcomes.

?
Decision making. Stochastic outcome

- How to quantify the goodness of the stochastic outcome?
  We want to compare it to deterministic and other stochastic outcomes.

![Diagram of stochastic outcomes](image)

Idea: **Use the expected value of the outcome**

---

Expected value

- Let $X$ be a random variable representing the monetary outcome with a discrete set of values $\Omega_X$.
- **Expected value** of $X$ is:
  $$E(X) = \sum_{x \in \Omega_X} xP(X = x)$$

**Intuition:** Expected value summarizes all stochastic outcomes into a single quantity.

- **Example:**

  ![Diagram of Stock 1 option](image)

- What is the expected value of the outcome of Stock 1 option?
Expected value

- Let $X$ be a random variable representing the monetary outcome with a discrete set of values $\Omega_X$.
- **Expected value** of $X$ is:
  \[ E(X) = \sum_{x \in \Omega_X} x P(X = x) \]
- **Expected value** summarizes all stochastic outcomes into a single quantity

- **Example:**

![Diagram showing expected value for Stock 1 option]

Expected value for the outcome of the Stock 1 option is:
\[ 0.6 \times 110 + 0.4 \times 90 = 66 + 36 = 102 \]

---

Expected values

**Investing $100 for 6 months**

![Diagram showing expected values for different investments]

\[ 0.6 \times 110 + 0.4 \times 90 = 66 + 36 = 102 \]
Expected values

Investing $100 for 6 months

- **Stock 1**
  - 102 (up)
  - 0.6
  - 110 (down)
  - 0.4
  
- **Stock 2**
  - 104 (up)
  - 0.4
  - 140 (down)
  - 0.6

- **Bank**
  - 1.0
  - 80

- **Home**
  - 1.0
  - 100

\[
\begin{align*}
0.6 \times 110 + 0.4 \times 90 &= 66 + 36 = 102 \\
0.4 \times 140 + 0.6 \times 80 &= 56 + 48 = 104 \\
\end{align*}
\]

M. Hauskrecht
Expected values

Investing $100 for 6 months

- **Stock 1**: 0.6 (up) 0.4 (down)
  - 110
  - $0.6 \times 110 + 0.4 \times 90 = 66 + 36 = 102$

- **Stock 2**: 0.4 (up) 0.6 (down)
  - 140
  - $0.4 \times 140 + 0.6 \times 80 = 56 + 48 = 104$

- **Bank**: 1.0
  - 101
  - $1.0 \times 101 = 101$

- **Home**: 1.0
  - 100

M. Hauskrecht
Expected values

Investing $100 for 6 months

<table>
<thead>
<tr>
<th></th>
<th>Stock 1</th>
<th>Stock 2</th>
<th>Bank</th>
<th>Home</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>102</td>
<td>104</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>104</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.4</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(up)</td>
<td>(down)</td>
<td>(up)</td>
<td>(down)</td>
<td>(up)</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>140</td>
<td>80</td>
<td>101</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>140</td>
<td>80</td>
<td>101</td>
</tr>
<tr>
<td>0.6 \times 110 + 0.4 \times 90 = 66 + 36 = 102</td>
<td>0.4 \times 140 + 0.6 \times 80 = 56 + 48 = 104</td>
<td>1.0 \times 101 = 101</td>
<td>1.0 \times 100 = 100</td>
<td></td>
</tr>
</tbody>
</table>

Selection based on expected values

The optimal action is the option that maximizes the expected outcome:

<table>
<thead>
<tr>
<th></th>
<th>Stock 1</th>
<th>Stock 2</th>
<th>Bank</th>
<th>Home</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>102</td>
<td>104</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>102</td>
<td>104</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.4</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(up)</td>
<td>(down)</td>
<td>(up)</td>
<td>(down)</td>
<td>(up)</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>140</td>
<td>80</td>
<td>101</td>
</tr>
<tr>
<td>110</td>
<td>90</td>
<td>140</td>
<td>80</td>
<td>101</td>
</tr>
</tbody>
</table>

M. Hauskrecht
Relation to the game search

- **Game search:** minimax algorithm
  - considers the rational opponent and its best move
- **Decision making:** maximizes the expectation
  - play against the nature – a stochastic non-malicious “opponent”

(Stochastic) Decision tree

- **Decision tree:**

  - decision node
  - chance node
  - outcome (value) node
Sequential (multi-step) problems

The decision tree can be built to capture multi-step decision problems:

• Choose an action
• Observe the stochastic outcome
• And repeat

How to make decisions for multi-step problems?

• Start from the leaves of the decision tree (outcome nodes)
• Compute expectations at chance nodes
• Maximize at the decision nodes

Algorithm is sometimes called expectimax

Multi-step problem example

Assume:

• Two investment periods
• Two actions: stock and bank

![Decision Tree Diagram]

M. Hauskrecht
Assume:

- Two investment periods
- Two actions: stock and bank

Multi-step problem example

Assume:

- Two investment periods
- Two actions: stock and bank
Multi-step problem example

Assume:
• Two investment periods
• Two actions: stock and bank

```
Stock  Bank
150  125  150  95  110  105
(up)  (up)  (up)  (down) (up) (down)

117  125  95  90  110  105
(up)  (up)  (down) (down) (up) (down)
```

M. Hauskrecht
Multi-step problem example

Assume:
• Two investment periods
• Two actions: stock and bank

• Notice that the probability of stock going up and down in the 2nd step is independent of the 1st step (=0.5)
Conditioning in the decision tree

- But this may not hold in general. In decision trees:
  - Later outcomes can be conditioned on the earlier stochastic outcomes and actions

Example: stock movement probabilities. Assume:

\[
P(1^{\text{st}}=\text{up}) = 0.4 \\
P(2^{\text{nd}}=\text{up}|1^{\text{st}}=\text{up}) = 0.4 \\
P(2^{\text{nd}}=\text{up}|1^{\text{st}}=\text{down}) = 0.5
\]


Tree Structure: every observed stochastic outcome = 1 branch

\[
P(1^{\text{st}}=\text{up}) = 0.4 \\
P(2^{\text{nd}}=\text{up}|1^{\text{st}}=\text{up}) = 0.4 \\
P(2^{\text{nd}}=\text{up}|1^{\text{st}}=\text{down}) = 0.5
\]
Trajectory payoffs

- Outcome values at leaf nodes (e.g. monetary values)
  - Rewards and costs for the path trajectory

**Example:** stock fees and gains. **Assume:**
Fee per period: $5 paid at the beginning
Gain for up: 15%, loss for down 10%

```
(1000-5)*1.15 = 1145
(1145-5)*1.15 = 1310.14
```

Constructing a decision tree

- The decision tree is rarely given to you directly.
  - Part of the problem is to construct the tree.

**Example:** stocks, bonds, bank for k periods

**Stock:**
- Probability of stocks going up in the first period: 0.3
- Probability of stocks going up in subsequent periods:
  - P(kth step=Up | (k-1)th step =Up) = 0.4
  - P(kth step =Up | (k-1)th step=Down) = 0.5
- Return if stock goes up: 15% if down: 10%
- Fixed fee per investment period: $5

**Bonds:**
- Probability of value up: 0.5, down: 0.5
- Return if bond value is going up: 7%, if down: 3%
- Fee per investment period: $2

**Bank:**
- Guaranteed return of 3% per period, no fee